



A wide dynamic range laser rangefinder with cm-level resolution based on AGC amplifier structure

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ABSTRACT

A pulsed time-of-flight (TOF) laser rangefinder with a pulsed laser diode and an avalanche photo diode (APD) receiver is constructed and tested. Triggered by an avalanche transistor, the laser diode can emit a periodic pulse with rise time of ~ 2 ns. A new structure with auto gain control (AGC) circuits both in the pre-amplifier and the post-amplifier is presented. Through this technology, not only the dynamic range of the receiver is extended, but also the walk error of timing discriminators is reduced. Large measurement range from 5 m to 500 m is achieved without any cooperative target. The single-shot precision is 3 cm for the weakest signal. Compared with previous laser rangefinders, the complexity of this system is greatly simplified.

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1. Introduction

Pulsed time-of-flight (TOF) laser rangefinder has attracted great interest in speed measurement and traffic control, three dimensional profiling and scanning, etc. [1–4]. Pulsed TOF laser rangefinder is based on measuring the round-trip time interval between emitted pulse and reflected pulse. Common structure of an TOF laser rangefinder consists of five major components: a laser diode transmitter, a receiver channel (PIN and APD photodiodes, pre-amplifier and post-amplifier), a timing part (two time discriminators and a time-to-digital converter), transmitting and receiving optical systems, and a micro control unit (MCU), as illustrated in Fig. 1.

In order to achieve a single-shot precision of cm-level, the rise time of the laser diode transmitter must be as short as possible. Moreover, The receiver bandwidth should match rise time of the laser pulse and always should arrive to several hundreds of mega-Hz [5]. To realize high sensitivity under such a big bandwidth, fixed receiver gain with large trans-impedance and high voltage magnification is inevitably required. However, due to the large dynamic range in some applications, this structure may bring about two vital problems. At first, since the reflected signal at a small distance is large, large fixed gain may force the output of the receiver to clip, which is equivalent to broadening the pulse width. Furthermore, because the reflected signal amplitude at different distances varies significantly, it will introduce large walk error in the time discriminator [6]. To solve the trade-off between wide dynamic range and high sensitivity, several technologies were used in previous researches, such as Gilbert cell [7], unipolar

to bipolar conversion [8], and compensation for walk error [9]. Unfortunately, system structures in these technologies are always complex.

Auto gain control (AGC) technology has been proved to be an effective method to extend the dynamic range of the optical receiver without deteriorating the bandwidth and signal-to-noise ratios [10–12]. In this paper, we apply the AGC technology in both the pre-amplifier and the post-amplifier of the laser rangefinder. Compared with former structures, the complexity and price of this system is immensely reduced. Large measurement range from ~ 5 m to ~ 500 m and high measurement accuracy of ~ 1 cm are attained. The specific design of the laser diode transmitter and the whole receiver channel is presented in Sections 2 and 3, respectively. The experiment results are given in Section 4.

2. Laser pulse transmitter

Both the MOSFET and the avalanche transistor are good choices to drive laser diode for generating short optical pulse. Unfortunately, due to the large gate capacitor, MOSFET is only capable for current trigger pulse with rise time above 3 ns. Compared with the MOSFET, avalanche transistor is suitable for shorter current trigger pulse. But it requires high voltage to ensure breakdown of the avalanche transistor [13]. In this paper, we employ a commercially available avalanche transistor (Zetex FM417) to drive an InGaAs pulsed laser diode (Perkin Elmer PGA3S06). The basic structure of the laser transmitter is illustrated in Fig. 2. The high voltage up to 250 V is provided by a switching power driver chip and a transformer.

The choice of discharge capacitor C2 and damping resistor R2 is crucial for expected performance of the transmitter. Larger

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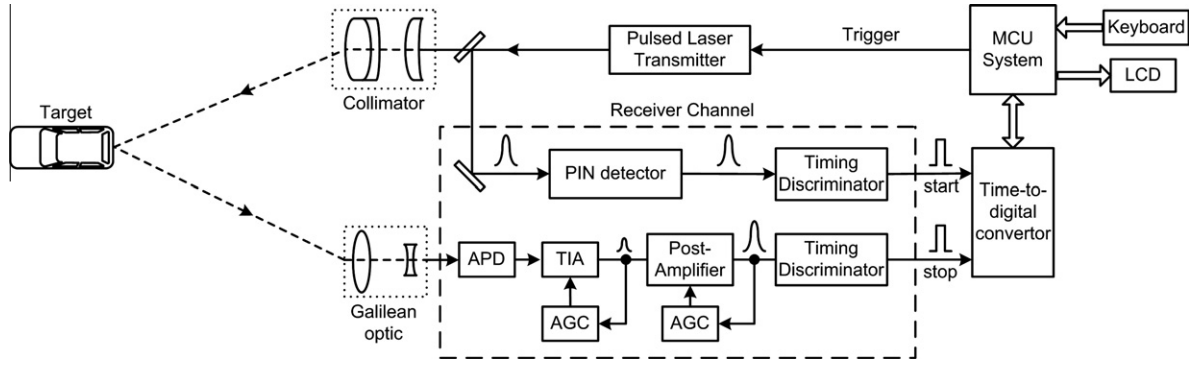


Fig. 1. Block diagram of the total laser rangefinder.

capacitance is good for high peak power operation, but simultaneously it will result in longer rise time and larger pulse width. On the other hand, the damping resistor R2 should be large enough; otherwise an unexpected reverse oscillation will appear. However, too large resistor will unfortunately lead to an asymmetry pulse waveform with longer fall time. In addition, to obtain small time constant, the inductors of the discharge circuit is controlled to be an extremely low level.

To minimize the spatial beam spread, a collimator lens (diam = 4 mm) is placed in the front of the laser diode. The optical pulse is detected by an ultrafast photo detector (Alphas UPD-200-SP, 2 GHz) and observed using a digital oscilloscope (YOKOGAWA DL9140, 1 GHz). The waveform observed on the oscilloscope is shown in Fig. 3. The 905 nm optical pulse possesses 70 W peak power and 2 ns rise time with pulse repetition frequency of 200 Hz. According to international standard (IEC 60825-1), the laser is Class 1 M device, which is safe for the human eyes.

3. Receiver channel

3.1. Total consideration

Three factors should be considered synthetically in the receiver channel design, which are bandwidth, signal-to-noise ratio and dynamic range. At first, the receiver channel bandwidth should match the rise time of the optical pulse ($BW = 0.35/tr$). In the other word, for the rise time of 2 ns, the receiver channel bandwidth should be at least 175 MHz. Second, the minimum signal-to-noise ratio of 10 is necessary for the receiver to satisfy the probability of detection and probability of false alarm. The main error of a pulsed TOF laser rangefinder called timing jitter error is determined by the bandwidth and signal-to-noise ratio of the receiver. The single-shot precision can be expressed as [14]

$$\sigma_R = \frac{0.35 \cdot c}{2 \cdot BW \cdot SNR} \quad (1)$$

where c is the speed of light, BW is the bandwidth of the receiver and SNR is the signal-to-noise ratio. Therefore, for the maximum detection distance, if the bandwidth of the receiver were set at 175 MHz, the idea single-shot precision of the laser rangefinder would be 3 cm. By statistical average of several pulses, the random timing jitter error can be decreased to a low level, and then the single-shot precision of the laser rangefinder can be improved to less than 1 cm. Finally, to avoid the system walk error due to clipping of the output signal, the receiver channel should have a large input dynamic range.

It should be noted that there are two other types of errors in the laser rangefinder. First, because the transmitting and receiving optical systems do not share the same axis, a system error called non-axial error will arise. Here, the distance between the two axes is just 5 cm. In this case, the non-axial error is so small that can be neglected. Second, due to the divergence of the incident beam, the pulse width will be undoubtedly widened in the single-shot detection. This will give rise to another system error increased with the distance. Considering the divergence angle of the indent beam is 3 mrad, the system error is calculated below 1 mm in the whole distance range.

3.2. Trans-impedance amplifier design

The trans-impedance amplifier (TIA) is the most difficult part to design because it is crucial to the noise feature and dynamic range of whole receiver channel. The predominant noise sources of the TIA are the thermal noise of the feedback resistors and the input-referred noise of the core amplifier. The input-referred noise current can be expressed as [15] (we neglect the influence of the input capacitor, and it does not significantly affect the subsequent analysis result.)

$$i_{noise}^2 = \left(\frac{4kT}{R_f} + \frac{V_n^2}{R_f^2} \right) BW \quad (2)$$

where k is the Boltzmann constant, T is the temperature, V_n is the input-referred noise voltage, and R_f is the feed back resistor. To obtain a high sensitivity at the maximum detection distance under such a big bandwidth (175 MHz), the feedback resistor should be as large as possible. Here, we chose a feedback resistor of 10 k Ohm that the input-referred current noise is controlled below 70 nA. The Lidar equation is employed to evaluate the noise level. For a planar Lambertian target, it can be expressed as [16]

$$P_r = \frac{\tau_a^2 \eta_r \rho_T P_t A_r \cos \theta}{\pi R^2} \quad (3)$$

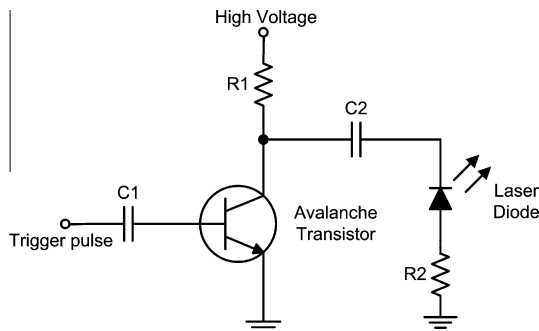


Fig. 2. The basic structure of the laser transmitter driven by an avalanche transistor.

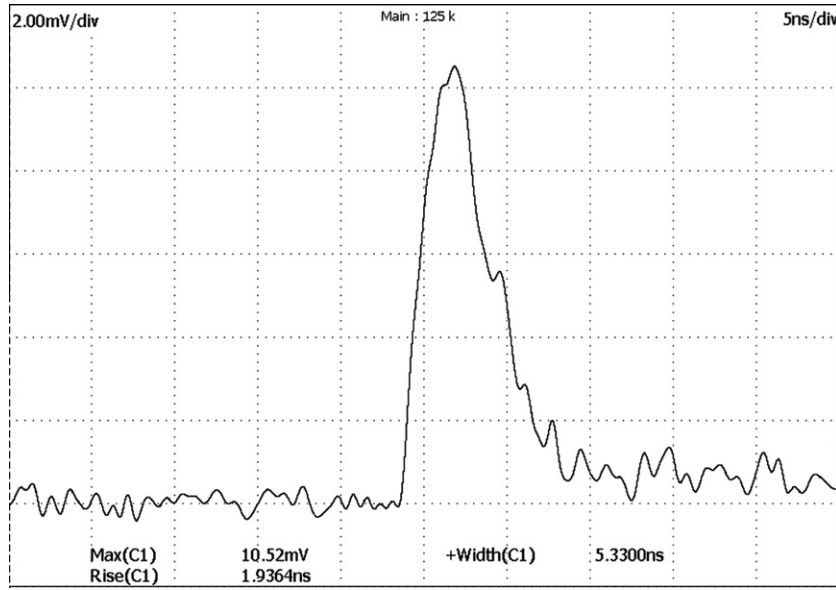


Fig. 3. Optical pulse waveform of the laser diode transmitter.

Table 1
Parameters for the Lidar equation.

Description	Value
Receiving optical system transmittance	70%
Target surface reflectivity	0.4
Telescope area (cm ²)	7.07
Measurement angle	≈0

where P_r is the received laser power, P_t is the emitted laser power, τ_a is the one-way atmospheric transmittance, η_r is the transmittance of the receiving optical system, ρ_T is the target surface reflectivity, A_r is the telescope area, θ is the angle between the laser beam and the target surface, and R is the distance between the target and the laser rangefinder.

For the wavelength region around 905 nm, the most important atmospheric absorber is the water molecule. Thus the atmospheric transmittance is undoubtedly related to the humidity and the temperature. Here, we suppose that the measurement is in the normal case that the temperature is 20 °C and the relative humidity is 50%. Then applying the method presented by Riedl [17] and Weichel [18], the one-way atmospheric transmittances through 500 m and 5 m path length are calculated at 94% and 99.4%, respectively.

Calculating the Lidar equation with the parameters given in Table 1, we can find out that the received laser power at 500 m away is 15.6 nW. The photo detector used here is AD500-9 (Silicon Sensor). It has a responsivity of 50 A/W at 905 nm wavelength. Thus the received photocurrent in the APD detector at 500 m away is about 780 nA, corresponding to a signal-to-noise ratio of 11. Consequently, the TIA feed-back resistor of 10 k Ohm can ensure the desired precision at 500 m away. Nevertheless, the large feedback resistor will force output of the TIA to clip when the target is close. This nonlinear response is equal to broadening the width of the optical pulse, and then the accuracy of the whole receiver channel will be deteriorated. Therefore, we establish an AGC trans-impedance amplifier structure, which is shown in Fig. 4.

The feedback resistors are made up of two parts: a fixed resistor of 10 k-Ohm and a MOSFET used as a variable resistor. A peak detector generates a DC voltage which will reflect the peak value of the TIA output. Once the input photo current is large enough, the DC voltage will exceed the threshold and force the MOSFET

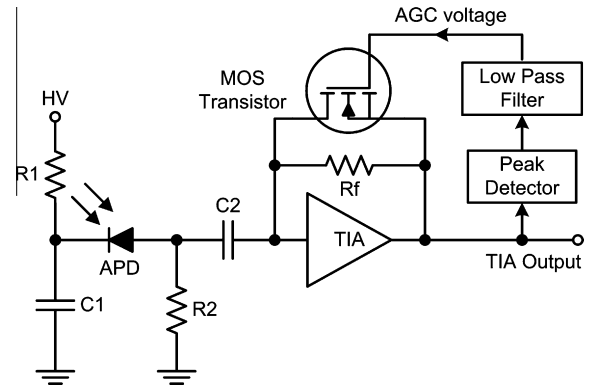


Fig. 4. Auto gain control structure of the trans-impedance amplifier.

to open. As the photo current increases, the DC voltage will increase correspondingly resulting in a decrease in the MOSFET resistance. In this case, the output of TIA will not clip over a wide input dynamic range.

The bandwidth of the TIA is associated with the feedback resistor, total input capacitor and amplification multiple of the core amplifier, which can be expressed as [19]

$$BW = \frac{A}{2\pi \cdot R_f \cdot C_{in}} \quad (4)$$

where A is the amplification multiple of the core amplifier, C_{in} is the total capacitor in the input node of the TIA, which include the capacitor of photo detector and input capacitor of the main amplifier. As seen from Eq. (3), The bandwidth varies from the feedback resistor. We should insure that the bandwidth is enough even when the resistor is large. Due to the large sensitivity area (500 μ m diameter), the capacitor of the photo detector is as large as 1.2 pF. To obtain a large bandwidth, the amplification multiple of the core amplifier is designed to 20, which is realized by three cascade stages structure. On the other hand, with the feed back resistor decreasing, the bandwidth and the input-referred noise will grow up synchronously. However, the signal-to-noise ratio will not be deteriorated due to the large signal in this case.

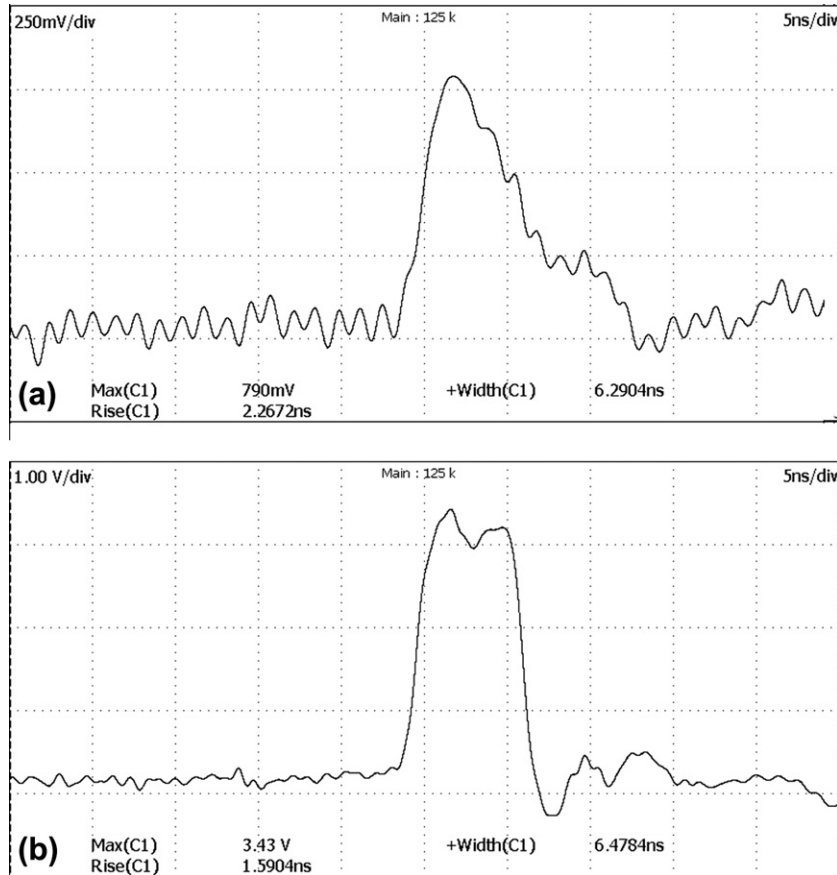


Fig. 5. The output waveforms of the receiver channel at the distance of 130 m: (a) the output voltage after the post-amplifier and (b) the output of the timing discriminator.

3.3. Other parts design

As a result of the AGC structure of the TIA, the output voltage range is compressed to a relative low level. However, the output voltage of the TIA still varies dramatically. If it directly accesses to a timing discriminator, two problems will arise. At first, the timing discriminator requires large input voltage amplitude to make effective comparison, but for the weakest signal, the output voltage of the TIA is not large enough. Second, the large input voltage range will introduce large walk error in the timing discriminator. In order to solve the above two problems, a variable gain post-amplifier with an AGC structure is exploited. After the post-amplifier, the dynamic range of the output voltage will be further narrowed.

The most simple time discriminator is the lead-edge time discriminator, but it requires the output of the amplifiers to be strictly an constant, which is difficult to achieve. In this system, we employ a time discriminator based on the method of constant fraction discriminator, which regards the midpoint of the lead edge as the timing point. Consequently, as long as the dynamic range of the input voltage range is under 10, a very low walk error will be achieved [20]. By the timing discriminator, the analog input voltage will be transferred to a TTL digital signal.

Time interval between emitted pulse and reflected pulse is measured by a time-to-digital unit. Traditional time interval measurement is based on either the direct counting method or digital interpolation method, and these methods are not appropriate for achieving high precision because of the restriction of the clock frequency [21]. Here, we use a commercially time-to-digital converter chip (Acam-messelctronic gmbh, TDC-GP1). This chip uses internal propagation delays of signals through gates to measure

time interval, so it has a very high precision reaching to 65 ps [22]. The measurement results are displayed in a LCD controlled by a micro-controller (Atmel, AT89C51).

4. Measurement results

An experiment is implemented to test the performance of the pulsed TOF laser rangefinder. A rough white paper is used as the target. Before the measurement, the axis of the transmitting and receiving optical system is adjusted to be parallel. Moreover, the sensitive area of the APD detector is also regulated to be at the focal plane of the receiving optical system.

At first, the bandwidth of the whole receiver is examined. Fig. 5 shows the received waveforms at a typical distance of 130 m. Fig. 5a is the output voltage after the post-amplifier and Fig. 5b is the output of the timing discriminator. It can be seen from Figs. 3 and 5 that the rise time changes little and the waveform is not distorted. The results indicate that the bandwidth of the whole receiver matches the rise time of the optical pulse. Consequently, even in the weakest case at the maximum distance, the single-shot precision is better than 3 cm.

Fig. 6 shows the trans-impedance gain versus the optical current of the APD. When the optical current is above 5 μ A, the AGC circuit is active and the feedback resistor will vary from 10 k Ohm to 100 Ohm. On the contrary, when the optical current is below 5 μ A, the AGC circuit is inactive and the feedback resistor will not change. At 5 m away, due to the non-coaxiality of the transmitting and receiving optical systems, there is only 40% of emitted laser entering into the receiver. According to the Lidar equation,

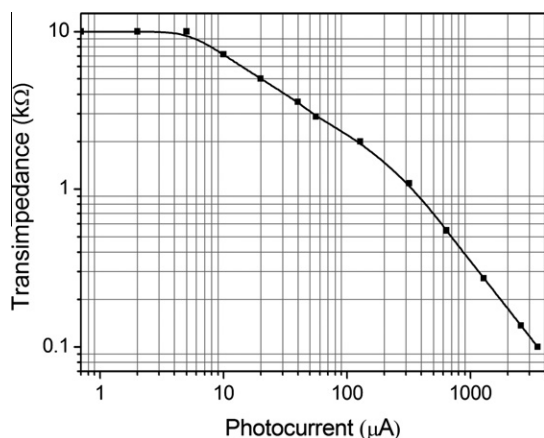


Fig. 6. Trans-impedance versus the input photo current of the pre-amplifier.

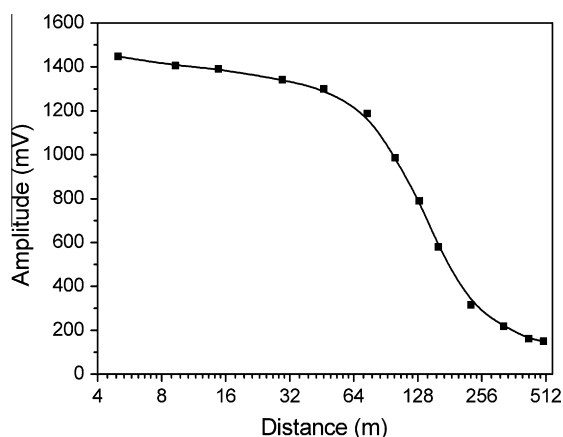


Fig. 7. The received signal amplitude after the post-amplifier versus the different detection range.

the input photo current at 5 m away is calculated at 3.5 mA. Therefore, for the whole dynamic range from 700 nA to 3.5 mA, the output voltage of the TIA ranges from 7 mV to 350 mV. The compression ratio of the TIA is as large as 100:1. If the distance is within 5 m, the output of the TIA will be clipped and the accuracy will be deteriorated.

Fig. 7 shows the received signal amplitude after the post-amplifier versus the different detection range. When the distance is within 50 m, the amplitude remains essentially constant and the influence of the AGC is obvious. In this case, the post-amplifier operates certainly in the nonlinear area. When the distance is beyond 50 m, the variation becomes large, but the decline rate is far less than the increase rate of distance. The post-amplifier gradually enter into the linear area, and the AGC does not work. For the distance range from 5 m to 500 m, the amplitude varies from 150 mV to 1.4 V. Generally, due to the combined effect of the

two AGC amplifiers in the receiver, the input dynamic range of 1:10,000 is compressed to 1:10. Experiment results show that by using the CFD timing discriminator, the walk error is below 100 ps, corresponding to a distance resolution of 1.5 cm.

Table 2 is a comparison between the presented TOF laser rangefinder with Aerius Photonics' product MLR100. As seen in it, the performance of this system is Superior to MLR100 [23].

5. Conclusion

We experimentally demonstrate and test a pulsed TOF laser rangefinder based on a laser diode transmitter and a wide range optical receiver. Driven by a commercially avalanche transistor, the laser diode transmitter can emit a short pulse with 70 W peak power and 2 ns rise time. The dynamic range of the optical receiver is extended by applying AGC technology both in TIA and post-amplifier. Trans-impedance of the pre-amplifier can vary from 10 k Ohm to 100 Ohm relying on the input photo-current. Consequently, a wide input range of 1:10,000 is achieved without severe distortion of the signal.

With the CFD timing method, the time walk error of the optical receiver is controlled to be less than 100 ps over the whole detection dynamic range. For weakest signal at the maxim distance, the single-shot precision is 3 cm with a signal-to-noise ratio of 10. For the whole pulsed TOF laser rangefinder, an accuracy of ~1 cm is achieved by average of 10 measurements over a detection distance range from 5 m to 500 m. The accuracy can be further improved by increasing the repetition rate of the laser pulse and compensating for the walk error. Generally, the simplicity of this system is superior to previous laser rangefinder, and it will possess huge prospect in laser speed measurement and Lidar applications.

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Table 2
Performance summary of the time-of-flight laser rangefinder.

Designation	This system	MLR100
Pulse repetition rate	200 Hz	500 Hz
Peak power	70 W	60 W
Rise time	2 ns	3 ns–15 ns
Pulse width	5 ns	15 ns
Wavelength	905 nm	940 nm
Accuracy	Better than 3 cm	18 cm
Range	5–500 m	50–100 m
Detector	APD	PIN

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